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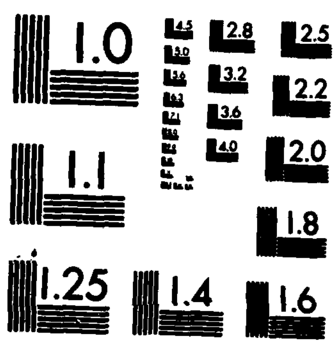

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Instrumentation Requirements for Small Scale Towed Temperature Measurements

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Ocean Dynamics Branch
Marine Technology Division

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Measurements of horizontal ocean temperature structure are difficult to obtain by towing sensors from research vessels because the tow cable induces sensor platform motions which contaminate the data. In this report, temperature data which previously were acquired in the thermocline with special care are used to specify the acceptable level of motion and to prescribe appropriate sensor noise levels. In the swell-induced ship motion band, for example, the rms vertical displacements of the sensors should be less than several centimeters and temperature sensors should resolve fluctuations of one millidegree Celsius in regions of high ($\sim 0.1^\circ C/m$) temperature gradient.

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INSTRUMENTATION REQUIREMENTS FOR SMALL SCALE TOWED TEMPERATURE MEASUREMENTS

CONTENTS

INSTRUMENTATION REQUIREMENTS FOR SMALL SCALE TOWED TEMPERATURE MEASUREMENTS

INTRODUCTION

In order to measure horizontal ocean fluctuations of temperature and salinity from research vessels of opportunity, the Ocean Measurements Program of NORDA has supported feasibility studies for appropriate towed systems. A preliminary study by Koeppen (1979) has evaluated a number of available towed systems to determine their suitability within a broad matrix of characteristics and has concluded that one or more existing systems can meet the requirements. That report was quite useful because it assembled and compared information on many towed systems which were developed over the previous decade. More recent reviews of specific towed systems have appeared (Nasmyth, 1980; von Zweck, 1980; Mesecar and Wagner, 1981), but specifications for the limits of motion of the platform and for the sensor resolution have not been made.

In this report, these two subjects are discussed in some detail. Measurements of temperature and conductivity fluctuations acquired with the NRL towed array are used as the standard toward which any new systems should strive to surpass. Horizontal spectra in the band from 1.5 cm to hundreds of meters are reviewed in some detail with the intent of using them as a model for the expected fluctuations. The lowest energy level in the model spectrum, then, is taken to be the minimum goal for any new system, since larger vertical motions of the instrument platform or higher noise level of the sensors clearly would contaminate the data. These measurements have all been made in the seasonal thermocline of the Sargasso Sea in the summer, so their universality is suspect. However,

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the energy levels are consistent with the Garrett and Munk (1972) model which was built upon a significant number of previous measurements. Thus, vertical fluid displacements and scalar fluctuations in other locations are assumed to scale with the local mean vertical scalar gradients in a known way. The requirements, then, are dependent upon local parameters. High vertical gradients forcce extremely tight tolerances on the allowable platform motions while small gradients push the sensor resolution requirement. The requirements also are functions of the bandwidth, as limited systems which resolve only part of the horizontal band can have somewhat more relaxed standards.

The usual approach to meeting the platform motion requirement has been to implement a motion isolation or compensation system (cf. Dugan et al, 1980, or Nasmyth, 1980). An alternative approach is to permit the instrument platform to heave in sympathy with the tow cable and to assimilate the tow spectrum from interpolation in a limited aperture vertical array. This approach is discussed and requirements for the vertical resolution of the array are specified by using available measurements of towed vertical coherence.

MODEL TOWED SPECTRUM

In this section, the tow data which will be used to specify allowable noise levels are presented. The data have been acquired previously by NRL by towing an array of thermistors and a high frequency conductivity sensor in the seasonal thermocline in the Sargasso Sea. Figure 1 shows towed temperature spectra in the horizontal band from one to several hundred meters. The different levels correspond to varying levels of activity in the data. The lowest energy level was in a region devoid of

significant features in the data, while the higher levels were in regions having energetic fine scale patches. The mean vertical temperature gradient in the vicinity of the measurements was 0.11°C/m.

In the same region, a high frequency conductivity sensor also was towed. Spectra of these towed conductivity data are shown in Figure 2 and, again, the various estimates have been obtained in patches having different energy levels. The mean vertical conductivity gradient was 0.13 mmho/cm/m (.013 S/m/m). These data have been discussed in more detail in Dugan et al (1983a).

Figure 3 is a combination of the data in Figures 1 and 2, and the spectra have been normalized by their respective mean vertical scalar gradients. The resulting spectra are estimates of displacement density and these are further multiplied by the square of the local buoyancy frequency so that the vertical scale, then, has units of potential energy density. It is arguable as to whether or not the fluctuations on the smaller scales, especially, represent actual fluid displacements from their equilibrium depths, but we will interpret the data in that way. On horizontal scales longer than several meters, more complicated algorithms for calculating displacements have been pursued and the results are consistent with these ones (Dugan et al, 1983b). For example, estimates of fluid displacements calculated from a high vertical resolution thermistor array by using the Eulerian estimation formula

$$d\zeta/dx = \frac{\partial T/\partial x}{\partial T/\partial z}$$

yield spectral levels within several dB of those in Figure 3. On scales less than the order of ten meters in the horizontal, the physical

processes which occur are mixing in nature, and the interpretation of these estimates as real fluid displacements clearly is invalid. Just how incorrect the estimates are, and of what sign a correction would be, is unknown. Thus, for the present, the interpretation of the variance distribution as fluid displacements all across the bandwidth in Figure 3 is assumed to be valid. In this interpretation, then, any sensor motion must be less that the lowest natural ocean fluctuation level in order not to contaminate the measurement. Thus, the lowest curve in Figure 3 is taken to be the maximum allowable instrument platform motion in the vertical direction.

The horizontal band in which platform motion typically is most severe is from about 10 to 30 meters. This is dependent upon the tow speed and the direction of tow with respect to the dominant component of swell. As an example, Figure 4 shows typical temperature displacement spectra plotted with the spectra of the vertical platform motion measured by pressure sensors. The temperature data exceed the motion level comfortably except in the motion band. In this band, the estimates are uncomfortably close (less than ~ 3db) and the system is performing at only a marginally acceptable level. This level of performance is not adequate in the quietest regions of the thermocline, as the ocean temperature spectrum drops down below this motion peak. The crucial point is that the rms platform motion is less than 2 cm in this band. Platform motions higher than this level clearly contaminate the quieter regions in the thermocline, and those a decade higher in variance level contaminate even the most active regions measured with the present system.

The remaining issue is with what confidence we project these results to be valid for other depths and other locations. Over the seasonal

thermocline in which the measurements illustrated in Figure 3 were made, the mean level of temperature displacement estimates varied by less than a factor of about two in a mean vertical temperature gradient which varied by a factor of about ten. Thus, to a first approximation, the rms displacement was constant across the thermocline. These results also are consistent with those acquired in previous years in the same location and season (cf. Bell et al 1975; Bell 1976; Miklovic 1981). However, the measurements reported by most other investigators are limited to bands outside that of the ship motion (cf. Moseley and Del Balzo 1976; Miropol'sky and Filyushkin 1971). Garrett and Munk (1972) have proposed a model for internal wave spectra in which the horizontal dimension was fitted to larger scale data of LaFond and LaFond (1971) and Charnock (1965). More recent results on the shorter scales by McKean and Ewart (1974) and Zenk and Katz (1975) as well as the data in Figure 3 are consistent with this model. In this model, the spatial spectrum is red and, although more recent variants have suggested several different possible colors, the energy level is assumed to scale as

$$N \langle \zeta^2 \rangle = \text{constant},$$

where N is the local buoyancy frequency. For the rms level, this normalization implies a rather weak dependence upon the buoyancy frequency. Dugan et al (1983a) only found a factor of order two in level between the seasonal thermocline and the level in the main thermocline reported by Katz (1973), and this is consistent with the expression above. At the shorter scales, the level does not appear to scale with a gross environmental parameter such as the mean gradient (cf. Gregg 1977).

On balance then, across the horizontal scales of interest here,

there is no overwhelming evidence to expect large changes in level from those shown in Figure 3. In several horizontal bands of particular interest here, the rms motions are given in the following table.

Band	rms Motion
< 10m	< 1 cm
10 - 30m	2 cm
30 - 100m	7 cm
100 - 300m	20 cm

MOTION CONTAMINATION

As discussed in the previous section, Figure 4 shows typical examples of the sensor platform motion spectrum with the associated temperature displacement spectra. This level of performance was achieved only with a motion compensator in the towed system. The motion compensator is a passive device which is connected to the tow cable at the shipboard end and which maintains constant tension on the cable. As the ship's stern heaves up, cable is let out in order to maintain constant tension. This system has been successful in maintaining the 2 cm rms sensor motion level in the ship motion band in sea states up to five (Dugan et al 1980). In future systems, contamination of the data can similarly be minimized by implementation of an isolation system like this one. This is not a trivial matter, however, because the system consumes deck space and requires a source of high pressure air. This air is available on the USNS HAYES but it would have to be provided at additional trouble on ships of opportunity.

A possible alternative solution to this contamination problem is to

tow a high vertical resolution (HVR) array. This array would not be motion stabilized, but the horizontal (and two-dimensional) temperature fluctuation field would be assimilated from interpolation in the array. In principle, this can be accomplished as long as the precise position in space of all elements in the array are known and the vertical spacing and frequency response of the sensors in the array is sufficient to resolve the temperature fluctuations. The crucial issue for a practical system is the required vertical resolution in the array. If the resolution requirement is too stringent, the high cost and complexity of a large number of sensors makes this approach unattractive.

As it turns out, the vertical spacing which is required is a direct function of the horizontal wavelength which one wants to measure. Estimates of the required spacing can be obtained from measurements of towed vertical coherence of temperature fluctuations. Using an HVR array which was isolated from motion by the shipboard compensation system, vertical coherence measurements have been made for sensor spacing of 6 cm on up by Morris and Dugan (1982). Figure 5 is a synopsis of those results. The two lines represent the .3 and .7 levels of squared coherence, so the top left part of the figure is a parameter region of high coherence and the lower right part is a region of low coherence. The 6 cm spacing well resolves all horizontal wavelengths of 10 m and more and, in fact, this spacing is adequate. This resolution, then, is an appropriate one for resolving the two-dimensional structure in the ship motion band, and the data should be adequate for calculating the temperature field in rectilinear coordinates.

This prediction, however, must be tested before the requirement for

a motion compensator is relaxed. The HVR data previously collected by NRL have been reveiwed for their usefulness in testing this principle. Unfortunately, they have been found to be inadequate because the motion of the array in two dimensions was not measured carefully enough (pressure sensor noise level too high). Thus, it has not yet been proven that the principle works for real data collected under the appropriate conditions. There is an additional problem in that there is uncertainty in what happens to the data on shorter scales. Thus, although the prediction using the towed vertical coherence data was fairly straightforward for the ship motion band, just what happens to the data on the shorter scales is unpredicted and, in fact, unknown.

SENSOR NOISE LEVEL

Proper design of the measurement system requires careful specification of system performance parameters among which are dynamic range, resolution, and noise level. In the following, these parameters are evaluated in the context of presently available towed measurements of conductivity fluctuations in the seasonal thermocline. Temperature specifications follow identical reasoning.

It is assumed that data acquired by such a measurement system are to be in digital format to facilitate subsequent processing and analysis. A further assumption is that the system must measure conductivity across the whole range of oceanographic values, that is from 0 to 6.5 S/m. The approach is to define the noise floor due to quantization of the data by the digitization process, and then to define the resolution and sampling rate in light of towing speed and the signal characteristics of the oceanographic proccesses that are to be measured. An additional assumption is

that levels of sensor noise, electronic noise, and various forms of data contamination are at or below the quantization noise level.

Quantization noise results from the roundoff or truncation inherent to the digitization of an analog signal. The resulting variance may be expressed as:

$$\sigma^2 = \frac{(\Delta^E)^2}{12}$$

where σ^2 is the quantization noise variance anJ $\Delta^E = E/2^n-1)$ is the least count or quantization interval for a signal range E and binary word length of n bits.

Figure 6 is redrawn from Figure 2; recall that the various spectra range from quiet to moderately active signal levels in the 2-100 cm range of horizontal wavelengths. A $k^{-5/3}$ line is included as a quiet signal reference level. This is taken as an estimate of the signal level that a towed conductivity system must resolve. Superimposed on Figure 6 is a family of seven lines corresponding to quantization noise levels for digital word lengths of 12-24 bits assuming a typical 0-6.5 S/m conductivity sensor range. The k^{-1} slope is the result of normalizing the bandwidth-independent quantization variance σ^2 by the bandwidth k_c in computing a power spectral density. Thus, for $\sigma^2 = 10^{-6}(S/m)^2$, if $k_c = 1$ cpm, the spectral density is $\phi^2 = \frac{\sigma^2}{k_c} = 10^{-6}(S/m)^2$/cpm. If $k_c = 100$ cpm, then $\phi^2 = 10^{-8}(S/m)^2$/cpm.

The special case of a pre-emphasis (PE) filter is also shown for the 16 bit word length. The standard PE filter used at NRL has an amplitude transfer function:

$$G_{PE} = \frac{[1 + (\tau_{12} \cdot \tau_2) + \tau_{12}^2 + \tau_2^2]^{1/2}}{[1 + \tau_2^2][1 + \tau_3^6]^{1/2}}$$

where $\tau_{12} = f(\frac{1}{f_1} + \frac{1}{f_2}),\ \tau_2 = {}^{f}/_{f_2},\ \tau_3 = {}^{f}/_{f_3}$

and $f_1 = 0.25$ hz, $f_2 = 200$ hz, and $f_3 = 500$ hz.

This function has constant gain from dc to 0.25 Hz followed by a roll-up of 6 db/octave to 200 Hz. At 500 Hz there is a 3-pole Butterworth bandlimiting filter.

The variable gain increases the system resolution as:

$$\phi_{PE}^2 = \frac{E^2}{12 \cdot 2^{2n} f_c G_{PE}}$$

if the variance is dominated by the higher wavenumber component. From Figure 6, it is clear that the high gain near 200 cpm results in better than 25 bits of resolution, again assuming a 0-6.5 S/m sensor range.

As may be seen in Figure 3, the spectra on scales significantly longer than 1 meter rise considerably faster than the -1 slope of the noise level-bandwidth lines. Thus, specifications stringent enough to resolve the microscale, are sufficient to resolve the fluctuations on the longer scales.

The effect of variation of the mean vertical conductivity gradient on the spectra of Figure 6 has not been studied explicitly so there is reservation in the definition of quiet spectral levels. For reference, the data in Figure 6 were collected in a seasonal thermocline in which the mean vertical gradient was about .013 S/m/m.

Two specific cases of system performance are indicated on Figure 6.

In each case, only those fluctuation levels above and to the left of the heavy lines are resolved. In case A, a 2.5 cpm Nyquist wavenumber corresponding to 20 samples per second at an 8 knot towing speed is assumed with a 16 bit resolution. It is clearly inadequate by a full decade to resolve the quiet background signal at full bandwidth, though it should be quite adequate to resolve wavenumbers less than 1 cpm. In addition, due to the redness of the spectrum, the aliasing incurred with the use of a digitizer without an anti-aliasing filter (such as in the Neil Brown CTD system) is inconsequential.

In case B, a 6.25 cpm Nyquist bandwidth is assumed, corresponding to 50 samples per second at a towing speed of 8 knots. The resolution is 18 bits and, in addition, the sensor calibration range is halved to 3.2 S/m which increases the resolution to an effective 19 bits. The resolution is then adequate for the full bandwidth of the measurement. Reduction of the bandwidth to 2.5 cpm naturally increases this margin.

The 3.2 S/m sensor range is a departure from the initial assumption of a 6.5 S/m range. However, for a towed instrument it is felt that the end points of the range can be adjusted for the particular area of ocean to be measured. The added effort required for adjustment and calibration should be justified by the more complete resolution of the dynamic range of the microstructure signal.

The use of a pre-emphasis filter in this system clearly satisfies the need for resolution without the overhead of storing more than 16 bit words (2 bytes). There is, however, a compensating computational overhead which includes the de-emphasis of time series and/or the re-coloring of spectra. The relative merits of the two approaches clearly depend on the specific

application.

As was stated previously, the scope of this analysis does not encompass sensor and electronic noise, and contamination issues. The assumption was made that sensor and electronic noise levels are dominated by the quantization noise and that particulate contamination is a soluble analytic problem. This is not necessarily so. Previous experience with editing particulate noise from the data stream is based on well-sampled (500 Hz) data. The feasibility of a similar process being successful with undersampled (20 or 50 Hz) data rates is open to question.

Using the least energetic curve in the foregoing figures, the required noise level of the sensor can be established as discussed above. A synopsis of the required noise level for temperature and conductivity sensors is given in the following table. The wavelength L is the shortest scale resolved in the bandwidth, and the noise levels listed are the highest which are allowable (assuming that it is white).

	Noise Level	
L	Temp.	Cond.
50 m	10 m°C	10 μmho/cm
10 m	1 m°C	1 μmho/cm
1 m	300 μ°C	300 nanomho/cm
10 cm	100 μ°C	100 nanomho/cm
1 cm	40 μ°C	40 nanomho/cm

CONCLUSIONS

Platform stability and sensor noise level requirements have been addressed by using presently available tow spectra. The requirements are a strong function of the required bandwidth. If, for example, only wavelengths longer than 50 m were needed (ie., longer than the ship motion band), no motion compensation is required and the sensor noise level can be as high as 10 m°C. On the other hand, if the bandwidth extends to 1 m, motion compensation is required to reduce platform motion to 2 cm in amplitude, and the sensor noise level has to be less than 300 μ°C. These results could be weakly dependent upon gross environmental parameters like the mean vertical scalar gradient, but this dependence is untested. In addition, the use of a high vertical resolution array has been considered so that the platform motion requirements could be relaxed. A vertical resolution requirement of 10 cm has been established, but it has not yet been shown that this technique can be used in place of a motion compensator.

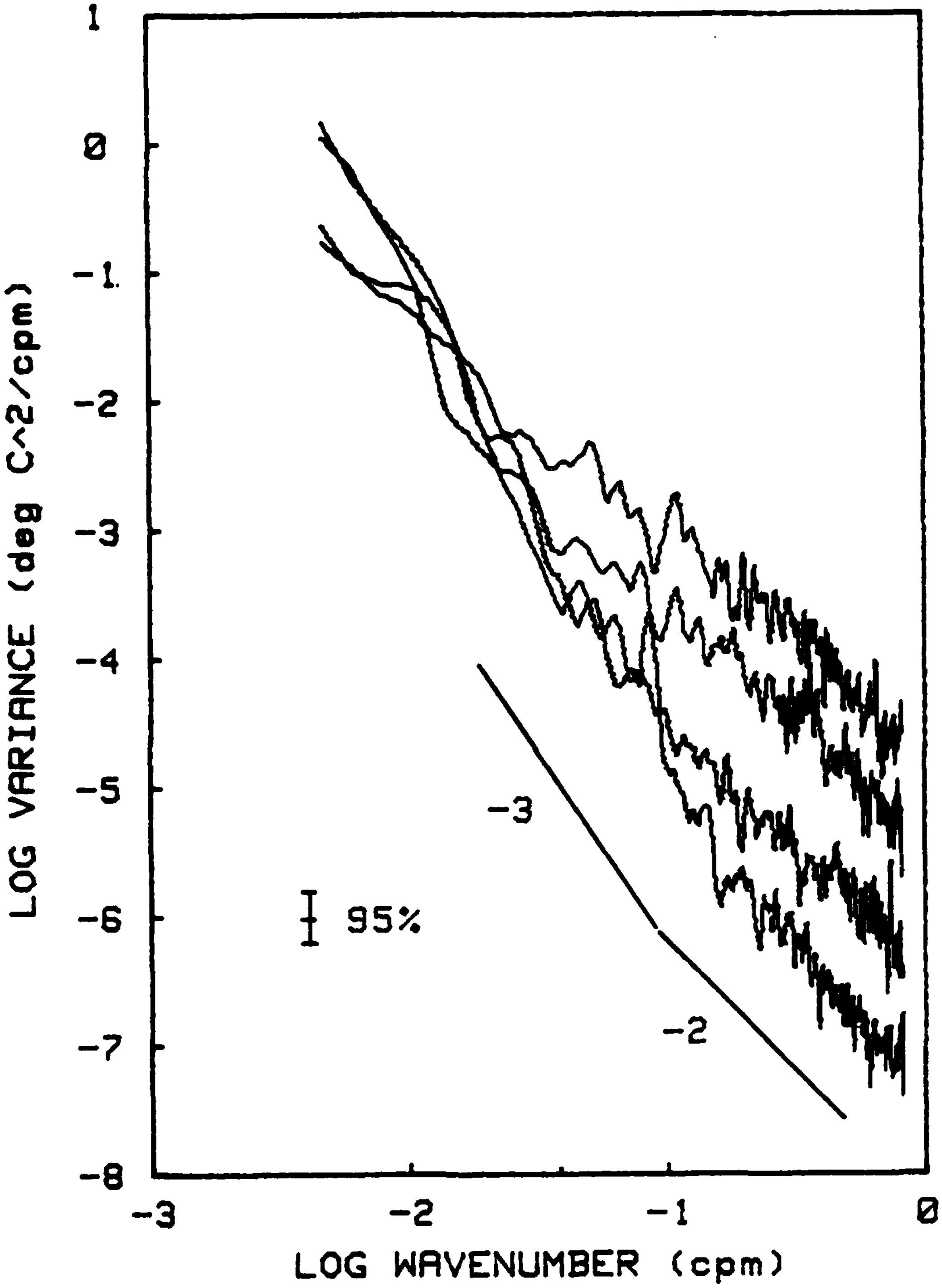

Fig. 1 — Towed temperature spectrum

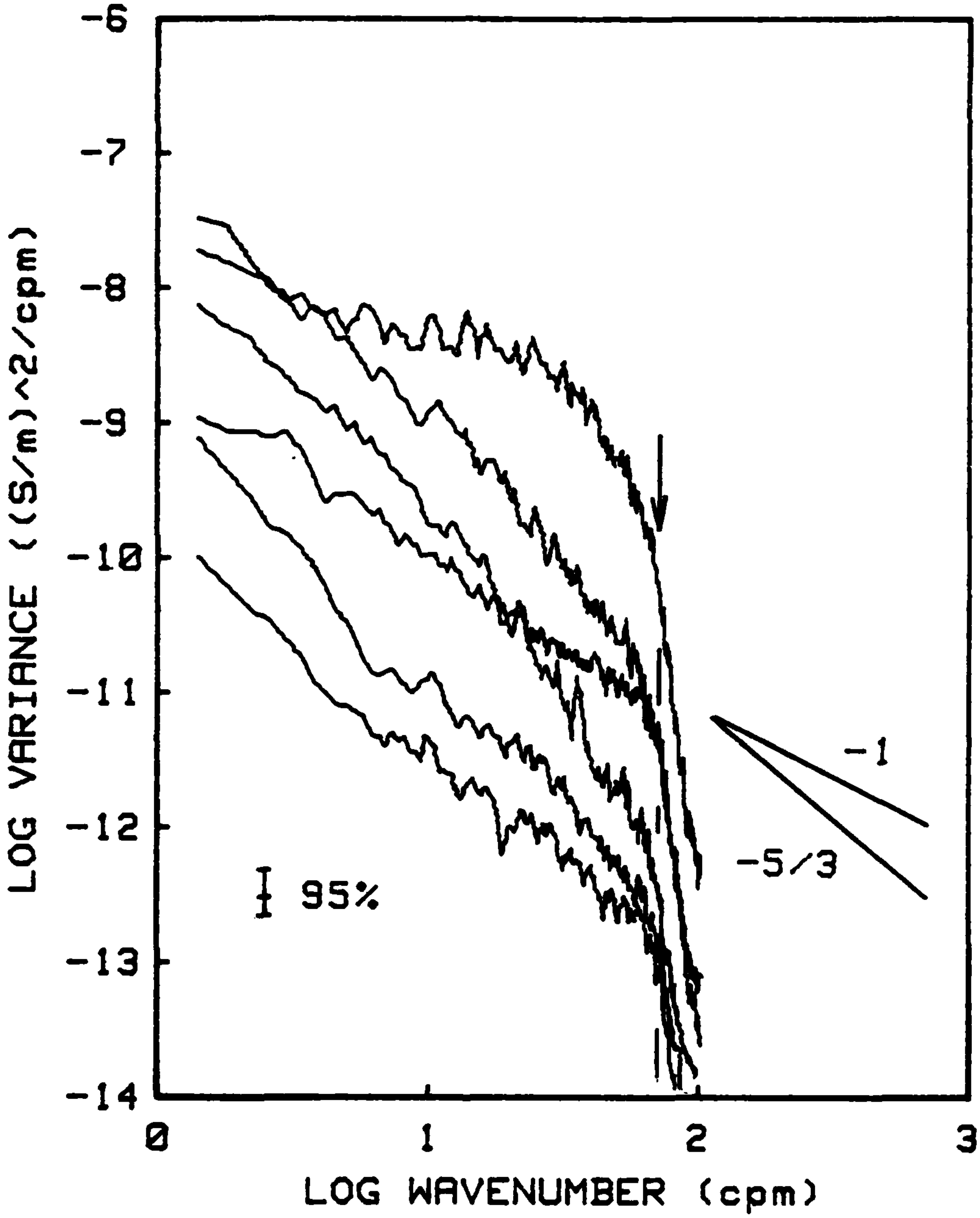

Fig. 2 — Towed electrical conductivity spectrum

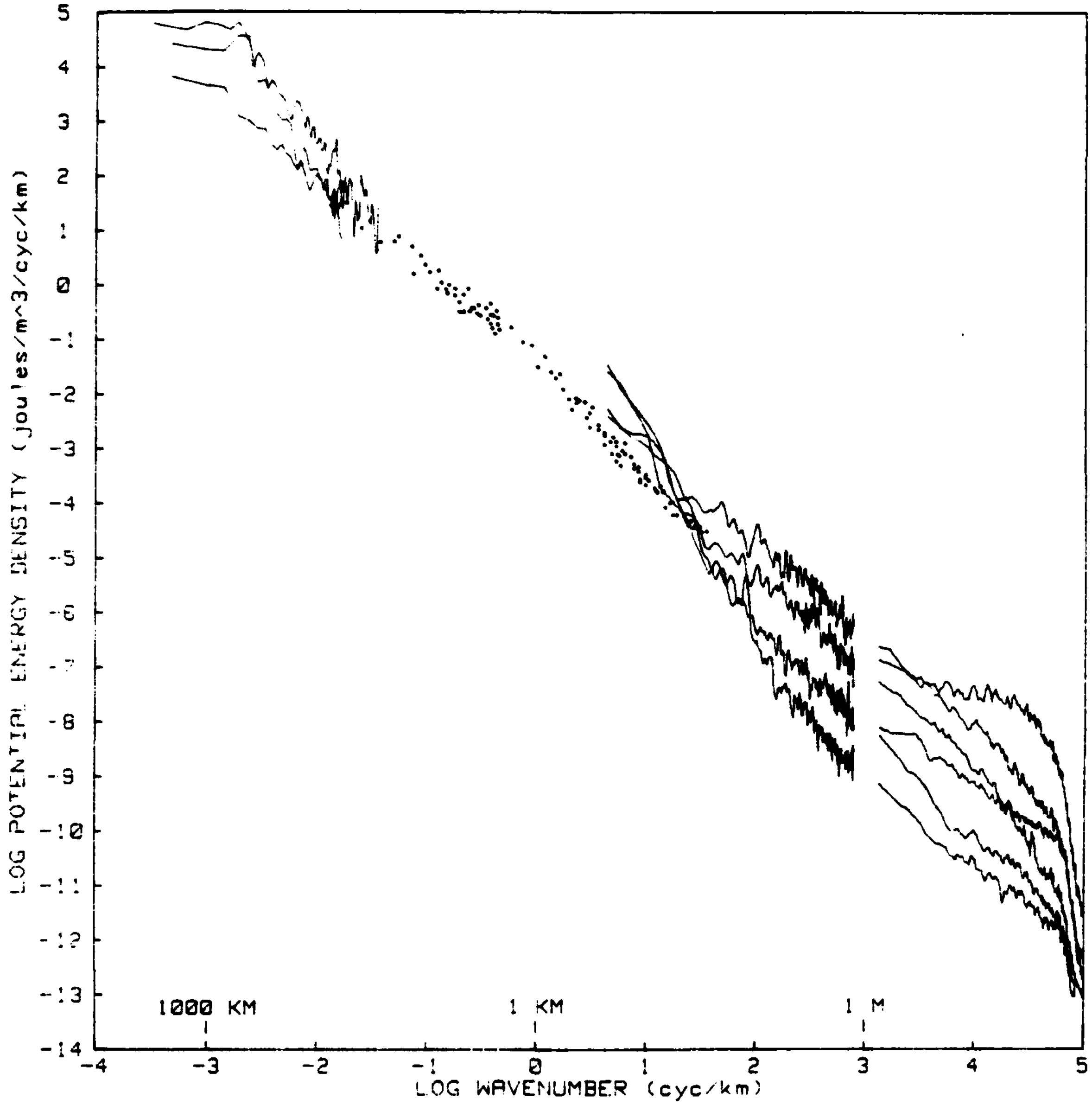

Fig. 3 — Composite horizontal spectrum using data from Figures 1 and 2

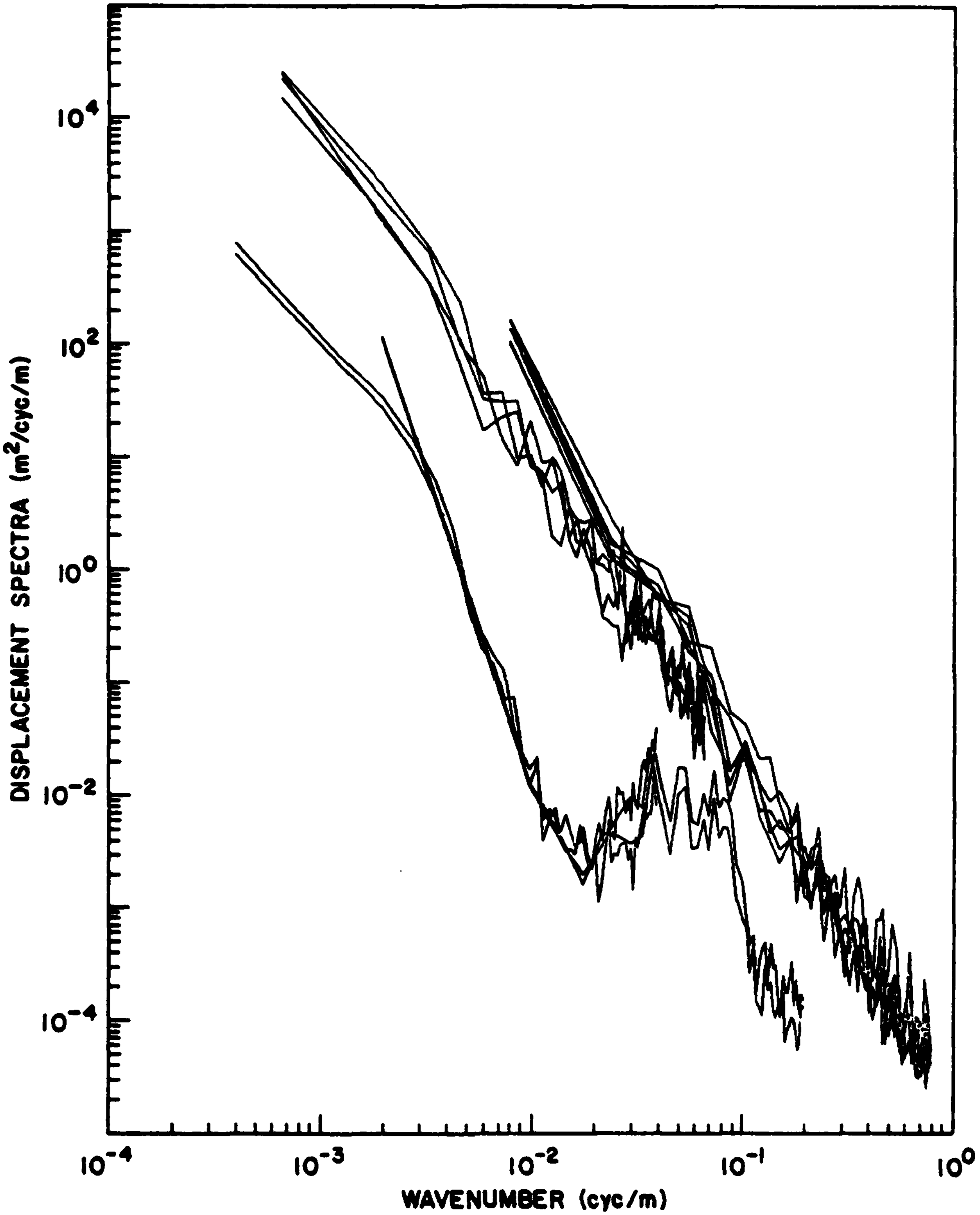

Fig. 4 — Typical towed temperature displacement and sensor displacement spectra

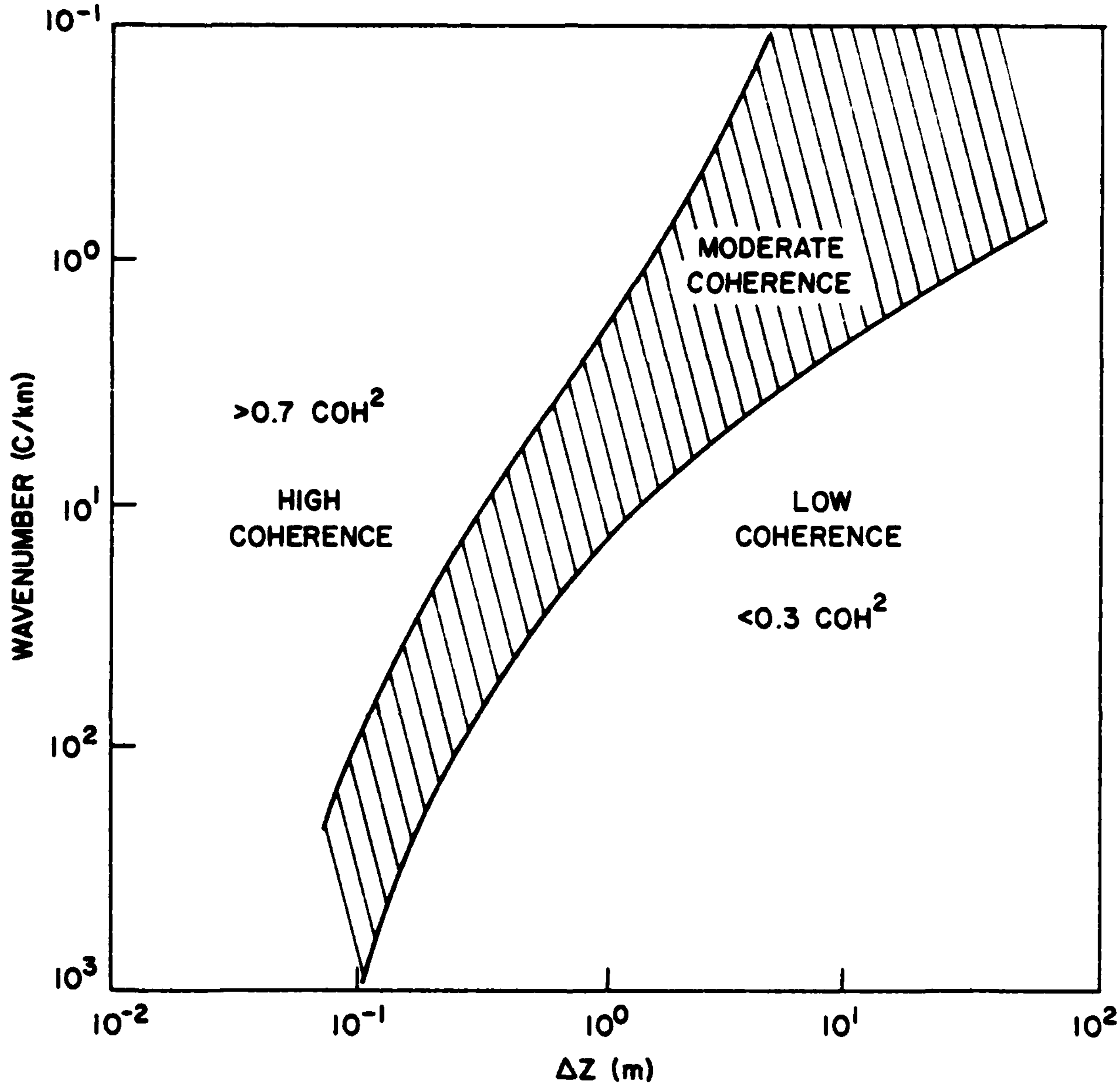

Fig. 5 — Towed coherence between vertically separated temperature sensors

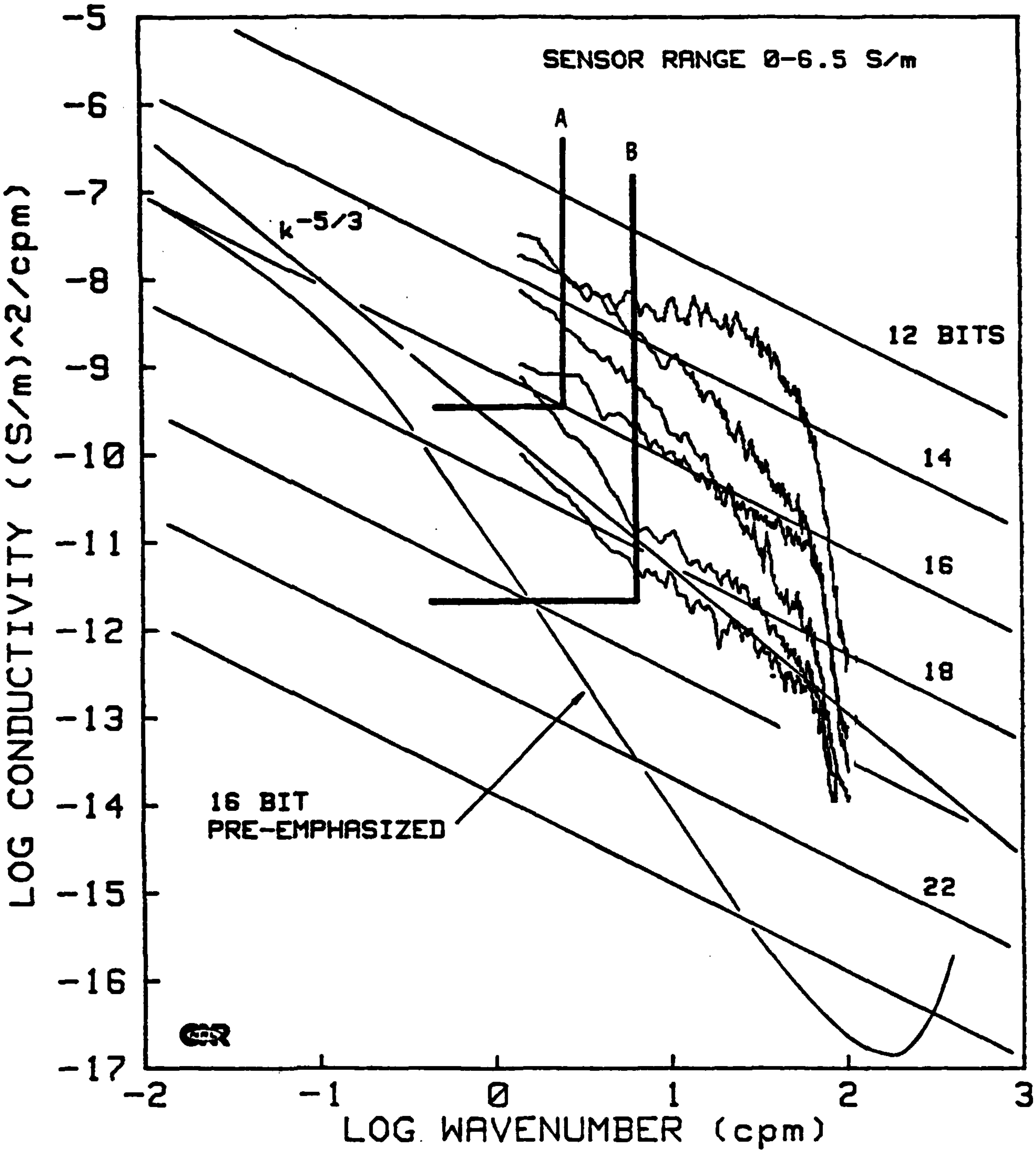

Fig. 6 — Conductivity spectrum, with various sensor noise levels

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